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Building performance evaluation and certification in the UK: Is SAP fit for purpose?

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ABSTRACT

Improving the efficiency and performance of the UK residential sector is now necessary for meeting future energy and climate change targets. Building performance evaluation and certification (BPEC) tools are vital for estimating and recommending cost effective improvements to building energy efficiency and lowering overall emissions. In the UK, building performance is estimated using the standard assessment procedure (SAP) for new dwellings and Reduced SAP (RdSAP) for existing dwellings. Using a systems based approach we show there are many opportunities for improving the effectiveness of BPEC tools. In particular, if the building stock is going to meet future energy and climate change targets the system driving building energy efficiency will need to become more efficient. In order to achieve this goal, building performance standards across Europe are compared highlighting the most effective strategies where they are found. It is shown that the large variance between estimated and actual energy performance from dwellings in the UK may be preventing the adoption of bottom-up energy efficiency measures. We show that despite popular belief, SAP and RdSAP do not estimate building energy efficiency but instead attempt to estimate the cost-effective performance of a building and thus create perverse incentives that may lead to additional CO_2 emissions. In this regard, the SAP standard confounds cost-effectiveness, energy efficiency and environmental performance giving an inadequate estimate of all three policy objectives. Important contributions for improving measurement, analysis, synthesis and certification of building performance characteristics are offered.

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1. Background

In the UK, buildings account for 46% of total CO_2 emissions, with the residential sector responsible for 27% of total emissions [1]. While space and water heating account for over half of total end use emissions [2], demand for electricity, driven by increased plug load, is growing faster than any other final energy source [3] (see Fig. 5). Such statistics emphasise the importance of

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Nomenclature

BPEC	Building performance evaluation and certification
BRE	Building research establishment
BREDEM	Building research establishment domestic energy model
CCC	Committee for climate change
DEA	Domestic energy assessor
DECC	Department of Energy and Climate Change
DER	Dwelling emission rate
DOE	Department of Environment
ECF	Energy cost factor
EHCS	English house condition survey
EI	Environmental impact rate
EPBD	Energy performance of buildings directive
EPC	Energy performance certificates
EST	Energy Saving Trust
EU	European Union
FES	Fuel and Energy Survey
FIT	Feed in Tariff
GDP	Gross domestic product
MS	Member States of the European Union
PV	Photovoltaic
RdSAP	Reduced Data Standard Assessment Procedure
RHI	Renewable heat incentive
SAP	Standard assessment procedure
SDLT	Stamp duty land tax
UK	United Kingdom
U-value	The overall heat transfer coefficient representing the rate of heat transfer through a physical boundary

reducing emissions from buildings for meeting future energy and climate change targets. This conclusion is defended by many international studies produced by multilateral organisations [2,4–9] and by government departments [10–14]. Moreover, there is overwheliming evidence from the extant literature, that some of the largest potential for emissions reductions are from buildings [15–23]. At the same time, improving the efficiency of buildings gives some of the lowest cost forms of CO_2 mitigation [24–28]. Yet, significant barriers and market failures undermine much needed investment in energy efficiency measures in the buildings sector [29].

In 2008, the UK introduced The Climate Change Act and thus became the first country to pass legislation for reducing GHG emissions. The UK is now legally bound to reduce emissions by 80% on 1990 levels by 2050 [30]. Interim carbon budgets established by the Committee on Climate Change (CCC) require 29% cuts by 2017; 35% cuts by 2022; and 50% cuts by 2027. While the interim budget to reduce emissions by 23% on 1990 levels by 2012 will be met, this did not occur directly due to climate related policy. Rather, the emissions reductions came from the 'dash for gas' during the 1990s [31] and the recent financial crisis that saw total emissions drop by some 10% in 2009 alone [32]. For the UK to meet the next set of carbon budgets, reductions in emissions from the residential sector are pivotal. This position is accutely expressed by the Committee on Climate Change (CCC) declaring net emissions from buildings in 2050 will have to be zero if future emissions targets are going to be met [33]. It is therefore evident that policy targeted at removing and overcoming market failures and barriers to investment are essential if progress towards reducing emissions from buildings is to be made.

1.1. Aim and scope of paper

The objective of this paper is to identify what characteristics of existing policy instruments are working well, and what factors may lead to larger and more rapid improvement of the building stock. A systems approach is applied requiring an assessment of the components within the system but also an assessment of the system as a whole. For example, existing government targets require all new buildings to be zero carbon by 2016 whilst simultaneously making significant improvements to the existing building stock (although there are no concrete targets yet in place for the existing stock). The effectiveness of policy therefore relies on the following system components:

- a universally accepted definition of zero carbon;
- accurate calculation procedures for assessing the performance of buildings;
- a widely understood building rating standard for the comparison and assessment of different buildings;
- a sufficient number of well trained and competent assessors to carry out inspections;
- a credible certification programme that when implemented will result in the rapid transformation of the building sector; and,
- high calibre research aimed at understanding the social and technical performance of the building stock resulting in new technological improvements and the development of more well informed policy.

Thus, a successful national BPEC strategy will have at its heart an accurate and reliable set of calculation procedures for assessing buildings; trained and competent assessors; an understandable and well-respected building performance and certification standard, and research with access to rich datasets to close the loop and further improve present BPEC standards. The need for a reliable measurement and verification system was demonstrated in the US through an analysis of the wide variance of energy and carbon performance of buildings under the LEED programme. In a study by Wedding and Brown [34,35] it was found the variance between estimated and actual energy consumption was caused precisely by the lack of measurement and verification in assigning green credentials.

The current paper is novel in its outlook and presents an original critique of building performance standards in the UK. It therefore offers an important but timely contribution to the development of policy for improving BPEC, thus leading to a deeper and more rapid transformation of the UK building stock. This paper is separated into four main sections. The first section looks at the development of BPEC calculation procedures in the UK. Here, we show how the evolution of BREDEM led to the creation of SAP and RdSAP and question the ability of existing SAP calculation procedures to deliver the changes necessary for meeting energy and climate change targets. The second section looks at the development of the EPBD and compares several different building standards implemented across Europe. Several improvements and strategies are identified for implementation within a UK context. Thirdly, we discuss energy performance certificates (EPCs) and the central role they play for driving bottom-up transformation of the building stock. Finally, we review the weaknesses of SAP and RdSAP and offer suggestions for how the

underlying calculation procedures may be improved, increasing the reliability of the estimates and therefore the predictability of end-use energy savings.

1.2. The importance of building performance evaluation and certification

Not only is it important that there is a sound evidence base for the potential contribution in emissions reductions from the residential sector, but also, the right policies and incentives are in place to ensure these reductions are achieved. One of the first steps required to meet future emisions related targets is to ensure a robust measurement and certification procedure is in place. There are many benefits for implementing a national BPEC and certification scheme several of these are discussed below.

- When statistically robust data is collected from a population of dwellings, it allows for detailed and accurate modelling of the existing building stock. With detailed information about the performance of a large number of discrete heteroenous buildings, data can be aggregated in different ways to determine the performance of buildings belonging to different groups. For example buildings can be broken into income deciles, building typology, ownership category or location etc. If only a limited sample was taken to represent the entire building stock, segmenting the sample would be difficult due to the limitations of sample size that may lead to erroneous conclusions about the performance of different groups.
- A large database containing information about each specific dwelling thus makes it possible to target whole boroughs, communities and streets for simultaneous improvement. Targeting the best improvements on a street-by-street basis means that resources can be pooled, transaction costs reduced and the benefits from economies of scale realised. Street-by-street transformation of the existing stock is a clear strategy supported by several existing studies [11,36–38]
- A national building performance and certification scheme provides a common standard from which all buildings can be compared and measured against (e.g. SAP, RdSAP, EPC's). This reduces confusion in the sector and improves market competition through increased disclosure of information.
- National certification schemes expose previously hidden information about a buildings performance. In Europe, it was not until the European performance of buildings directive (EPBD) that certification requirements were extended to existing buildings across the EU. A primary function of building certification is to address the issue of imperfect information and encourage much needed investment in building energy efficiency [39]. In Europe, an EPC needs to be produced every time a new occupier purchases or leases a building. Through the provision of information about a buildings' energy performance, new occupiers are given the opportunity to make well-informed choices about the property thus changing the characteristics that drive value in the property market.
- Fuel poverty in the UK is an increasing concern. In 2009, it was estimated that at least one-fifth (5.5 million) of UK homes were in fuel poverty [40]. This is only exacerbated by the forecasted increase to energy prices [41]. Without detailed information about the performance of buildings classified as being in fuel poverty, it is difficult to determine what strategies will be best at alleviating these pressures [42]. It is only through robust BPEC standards that the most effective strategies for improving energy efficiency can be identified and therefore increased opportunities for reducing fuel poverty can be targeted.

In sum, the successful implementation of BPEC standards are central to any national strategy for reducing emissions, lowering energy costs and improving fuel poverty. However, such benefits only accrue when BPEC standards are trusted by the users of the information. This can only occur if building performance and evaluation criteria are able to provide an accurate measure of a dwellings final energy consumption and emissions. In this paper we show how BPEC and certification standards can be improved through the provision of better evidence, incentives and targeted policy design.

2. Evolution of building performance evaluation procedures in the UK

Presently, the UK relies on a group of models (BREDEM) developed and maintained by BRE for estimating the energy consumption of UK buildings. BREDEM was established as an engineering simulation tool for estimating individual building performance. Typically a trained engineer or energy assessor performs an audit on the physical characteristics of a building through measurement and identification of energy relevant characteristics within the home. Parameters recorded include the surface area of all floors, walls windows and roofs as well as the materiality of the structure (e.g., insulation thickness and double glazing). Details about the energy system are also required to determine heating system efficiency. Calculation routines thus use internal and external temperatures to estimate energy demand from a set of heat balance equations [43]. As BREDEM is essentially a physical simulation model the data requirements are substantial.

It is from the early suite of BREDEM models that the standard assessment procedure (SAP) for assessing the performance of new dwellings was first created. The energy performance of existing buildings is estimated using the reduced standard assessment procedure (RdSAP) and is based primarily on SAP procedures. In RdSAP, additional standard data tables (using default values) are added to the model to replace missing or incomplete information. This greatly reduces the data requirements and the time required for carrying out building performance assessments on existing buildings. Unfortunately this often comes at the expense of accuracy when a building's performance is different from that of the category on which default values were obtained.

Although building regulations have been in place for newly constructed buildings for several decades, it is only relatively recently that existing buildings have come under much deeper scrutiny. This introduces its own set of complex issues. The UK suffers from an aging building stock where approximately 40% of buildings were built before 1944 [44]. Moreover, it is estimated

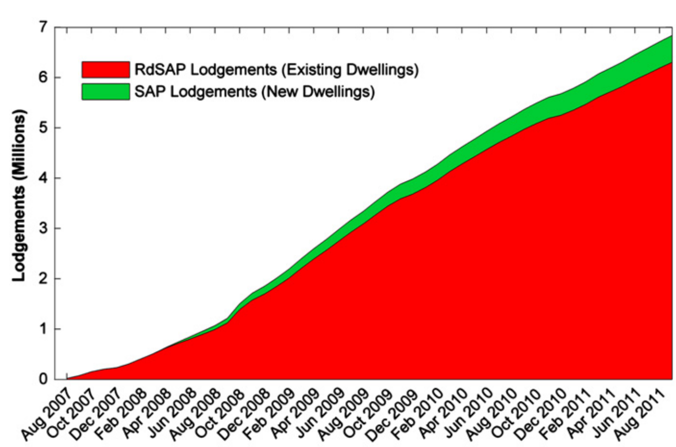


Fig. 1. Cumulative EPC lodgements in England. (Data source: Freedom of Information Request from LandMark (Phil Beschizza 2011)).

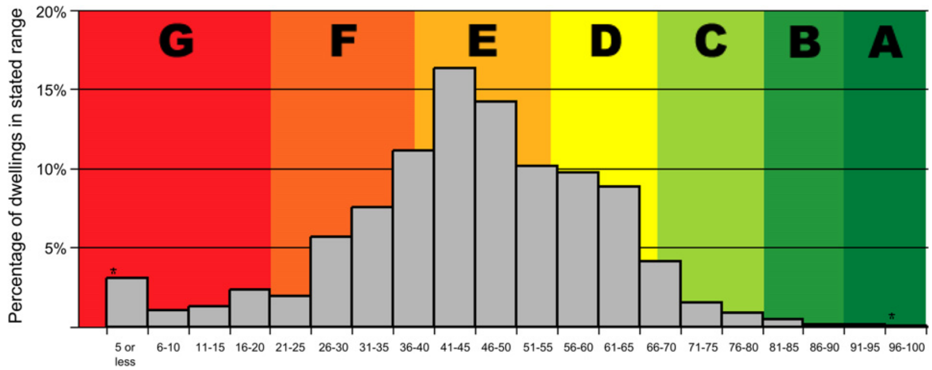


Fig. 2. Distribution of UK SAP ratings in 1996.
(*Data source*: EHCS 1996, after grossing weights have been applied).

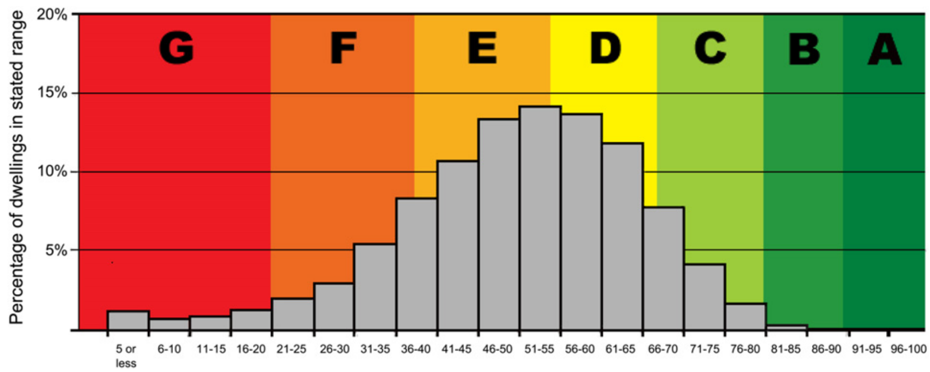


Fig. 3. Distribution of UK SAP ratings in 2006.
(*Data source*: EHCS 2006, after grossing weights have been applied).

that over 75% of buildings in use today will still be standing in 2050 [26,45]. Thus, transforming the existing building stock whilst maintaining high standards for the construction of new buildings, will be central to any national decarbonisation strategy. The importance of existing buildings is emphasised in Fig. 1 where the cumulative number of EPC lodgements from new dwellings and existing dwellings is compared. If present trends continue, all buildings will have an EPC by the early 1920s.

The UK Governments standard assessment procedure (SAP) was first developed in 1993 as an independent calculation methodology for estimating the performance of buildings across the UK. SAP is now at the heart of Government policy concerning the measurement, identification and improvement of the UK building stock. The SAP standard has now been fully incorporated into the UK building regulations for meeting the energy requirements of newly constructed buildings (Part L1A) and for measuring the energy performance of existing buildings (Part L1B). It is the chosen methodology for delivering the EU energy performance of building directive (EPBD) and is used in the calculation and creation of energy performance certificates (EPCs). It is used widely for the delivery of many Government policies such as Warm Front, the Carbon Calculator, Stamp Duty Exemption for Zero Carbon homes and The Code for Sustainable Homes among others. In future SAP will increasingly be used for the delivery of new Government policy targeting a reduction in emissions from dwellings across the UK. For example, SAP will likely play a central role in policy instruments such as the Green Deal and the renewable heat incentive (RHI), where the effectiveness of strategies to reduce energy and carbon will need to be assessed. Additionally, it will be an important measure for identifying and targeting homes requiring priority attention, such as those dwellings classified as being in fuel poverty.

The estimated performance of the building stock is also changing. In Figs. 2 and 3, two histograms represent how the estimated performance of the English building stock has evolved over a 10 year period from 1996 to 2006. While it is clear both the mean and the median estimated performance of dwellings has improved, there has been very little increase within the category of high performance buildings (A or B).[2] Clearly this must change if all buildings are to be zero carbon by 2050 as recommended by the Committee on Climate Change [33].

Given the importance of meeting future energy and climate change targets and the central role of buildings for meeting these goals, it is crucial that the underlying data and calculation procedures used by SAP are understood, validated and reflect the range of strategies that might be adopted to improve performance. Whilst anecdotal evidence from professional and academic circles suggests the efficacy of SAP for measuring building performance may be outdated and inadequate [46,47], there is a gap within peer-reviewed literature providing an independent critique for the effectiveness of BPEC for improving building stock emissions. There is also a serious lack of recent experimental analyses testing the validity and robustness of BREDEM and SAP (at least since 1990s) in regard to calculating building performance, especially for low energy buildings [48]. Such validation tests need to correctly estimate the effect of new efficiency measures on energy consumption while controlling for behavioural and other climatic factors. Furthermore, many newly constructed homes do not meet minimum regulatory compliance

[2] Changes to the SAP calculation methodology between 1996 and 2006 may be responsible for some of the variation in estimates.

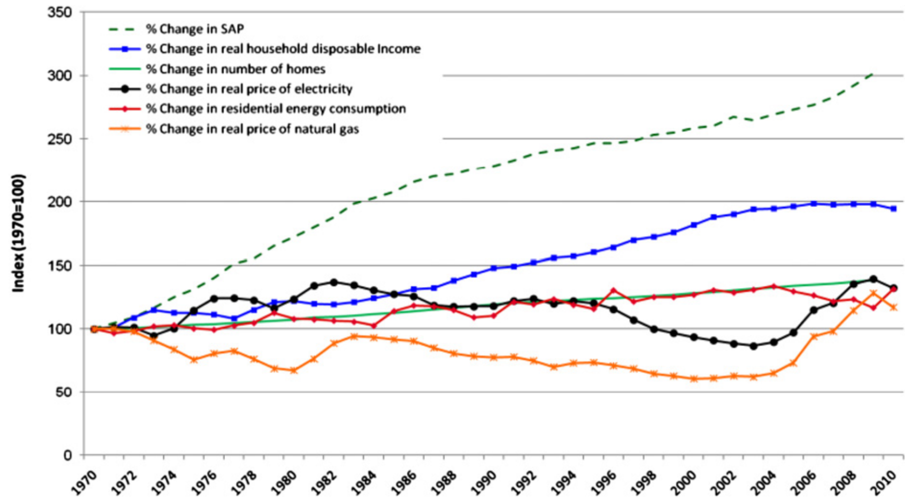


Fig. 4. Relative changes in factors that effect household energy consumption and SAP.
(*Data source*: DECC Domestic Energy Consumption in the UK Tables).

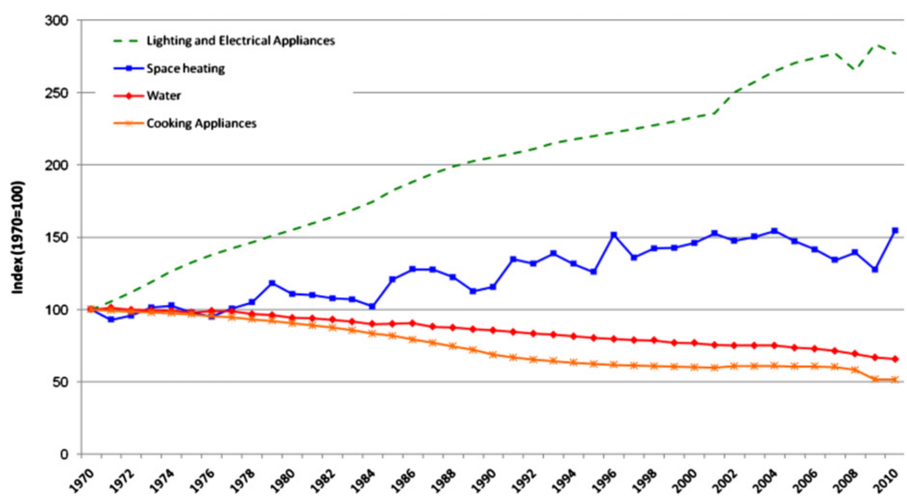


Fig. 5. Change in net energy consumption for different end use types.
(*Data source*: DECC Domestic Energy Consumption in the UK Tables).

standards [49]. This is owed to design errors, building defects and failures in enforcement. This is largely because of poorly developed policy, low understanding from those implementing the regulations and a lack of verification of performance [47].

As shown by Fig. 4, there has been tremendous growth in the relative SAP rating, rising from an average of just 18 in 1970 to 54 in 2010. If this trend continues, the average SAP rating of the UK building stock will increase to 88 by 2050. This is equivalent to an average dwelling reducing its energy bill from £720/annum to £192/annum in real terms using SAP2009 standard assumptions.[3] Although the trend for increasing SAP rates is promising, the corresponding rate of increase in energy consumption remains uncertain especially as real household disposable income is expected to rise. Furthermore, electricity is the fastest growing end-use energy carrier and presently has the highest carbon intensity (Fig. 5). Not surprisingly, the growth in residential energy consumption is largely matched by the growth in new dwellings for the period 1970–2004. From 2004 onwards however, residential energy consumption appears to decouple from growth in new dwellings. One plausible explanation for this sudden decoupling was the rapid rise in the real price of gas and electricity, from 2004 onwards motivating consumers to cut energy spending. Another point worth noting is that the real price of energy (gas and electricity) is only 20–30% more expensive in real terms than it was in 1970, where the majority increase in real energy prices has occured in the last five years.

In conclusion, SAP calculation procedures now form the backbone of government policy for estimating building performance in the UK [50]. It is the primary method for assessing the efficiency of the building stock and for meeting EU policy directives regarding improvements to building efficiency [51–53]. SAP is widely used by government departments, local authorities, architectural practices energy auditors and energy companies for estimating building performance and for meeting minimum

[3] Using the SAP2009 methodology it assumes an average dwelling in 2011 with a SAP rate of 55 and area of 60 m^2 consumes 15.5 MW h/annum for heating using natural gas at 3.1 p/kW h and 1.55 MW h/annum of electricity at 11.46 p/kW h. By 2050 the same home will improve its SAP rate to 88 leading giving an annual energy consumption of 4.2 MW h/annum for heating using natural gas and 2 MW h/annum for electricity at the same prices (£2005).

compliance regulations. Accordingly, the calculation procedures underpinning SAP need to legitimately estimate energy and emissions from buildings so accurate decarbonisation opportunities can be identified and implemented with minimal delay.

2.1. The early BREDEM models

During the 1980s an Energy World Demonstration project was initiated where 51 homes in the Milton Keynes Energy Park were designed and constructed to be at least 30% more efficient than the building codes of the time. These new building endeavours led to advanced trial and monitoring programmes and the construction of over a thousand new low energy homes across the UK. It represented a milestone in the design and construction of energy efficient buildings and important developments in the evaluation of whole-house energy calculation procedures.

These very first whole-house energy calculation procedures became an early predecessor to the BREDEM family of models. The first of these models was a single zone; bi-seasonal building physics model that utilised mean seasonal temperatures for the calculation of energy demand [54]. This approximation procedure averaged external temperature over the entire heating season (October to April inclusive [5.5–7.5 °C]) for use in a heat balance equation. Similar approximations were adopted for internal temperatures, estimated to be 16.4 °C for homes using full central heating and 13 °C otherwise. Clearly, these crude temperature approximations introduce significant uncertainty and adversely affect the model's ability to predict energy use across heterogeneous dwellings. Although these approximations simplified the calculation procedure, it is now widely accepted that internal energy demand is highly sensitive to small changes to both internal and external temperature, and that internal temperature is significantly affected by occupant behaviour, raising questions about the accuracy of this model for predicting energy demand [55]. Furthermore, the sensitivity of this model to varying climatic conditions has never been validated, as dwellings used to construct the model were taken from the same geographical area [54].

Another shortcoming of this early model was its sensitivity to the estimated length of the heating season, producing dramatically different demand estimations for small changes in heating season length. Although the temperatures used in this model were based on long-term averages and no considerations were made for the behavioural effects of occupants, an investigation into the validity[4] of the model showed model estimations were roughly within 20% of measured energy consumption values [56]. Unfortunately, the sample of homes used for this validation consisted of just 42 dwellings and had similar characteristics to the homes used during model development, limiting the statistical power of the model to be used for different building typologies and locations [56]. The homes modelled thus differ markedly in their characteristics from homes in the population bringing into question the applicability of the model to draw conclusions about the building stock more generally.

A later version of BREDEM was extended to include two zones within the dwelling and incorporated changes to the way internal and external temperatures were handled. Specifically, the model adopted the degree-day method instead of the mean temperature method [57]. The degree-day method is a better approximation of heating demand than the mean temperature method as it more accurately estimates climatic factors from both the duration and extremes of seasonal temperature profiles. Henderson [57] tested the two-zone version in BREDEM-5 against earlier versions of BREDEM and showed that the two-zone model improved the scatter of model estimates of energy consumption, reducing the standard error from 3.3 MWh to 2.8 MWh (12 GJ to 10 GJ). As noted by Shorrock [48] these improvements could have also been explained by other changes incorporated in the model at the same time. A further shortcoming of this validation process was that it used the same building dataset as was used by Uglow [56], and therefore is subject to the same limitations as discussed earlier. Such validation exercises raise important questions about the robustness of these early models for estimating building performance more generally. Furthermore, Henderson [57] notes:

"...Note that the sample used for this study was dominated by medium to large dwellings with a good standard of heating, so that the good agreement observed should be extrapolated only cautiously to other situations" [57, page 91]

Henderson remarks the model should be expanded and validated against a more varied range of dwellings. The paper proposes that fabric heat loss is only loosely related to energy consumption and calls for an assessment method that accounts for the demand for heating instead of an analysis of only building fabric (i.e., a model incorporating human behaviour). A description on the development of the BREDEM prior to 1985 is available in a report produced by Anderson et al. [58].

In BREDEM-8 the model was upgraded from a two-zone bi-seasonal version to a monthly model. Another validation exercise was completed by Dickson et al. [50] and involved comparing the results of the monthly model and the seasonal model against metered energy measurements and detailed simulation models. The metered energy measurement dataset used for this validation exercise consisted of just 19 intensively monitored dwellings from the Milton Keynes Energy Park over a period of two consecutive years [50]. All dwellings participating in this study used natural gas for central heating and were designed to consume 30% less energy than typical buildings constructed in the UK at the time. Once again, due to the confined geographic location of the sample and the limited sample size, the results from this validation exercise can only be cautiously extrapolated to buildings in the rest of the UK.

A major finding from Dickson [50] was very little difference between results from the bi-seasonal version and the monthly version of BREDEM. The reason for such agreement in model results is most likely due to similar assumptions made by the two models. For example, the monthly model adopted the same calculation procedure for estimating electricity demand as the seasonal model and simply divided the estimated annual electricity demand evenly over each month in the 12-month period. Dickson [50] also showed that BREDEM compared well with more detailed simulation models. Agreement between Dickson's BREDEM model and other building simulation models can be explained by similar assumptions common to most physical building simulation models. For example, building simulation models fail to account for human behaviour and usually just include the physical properties of the building along with average internal and external temperatures.

The most recent BREDEM model incorporated several needed improvements. The latest version of the model allows for different heating profiles for weekdays and weekends, a more thorough account of renewable resources, monthly demand estimates for electricity from lights and appliances, a more realistic representation of the responsiveness of heating systems and important corrections to the utilisation of hot water. Given the significant developments that have now been incorporated into BREDEM it is unfortunate that robust validation projects of the model have not been carried out for over 15 years. As discussed already, even the initial validation exercises conducted on BREDEM raise important questions about their applicability for extrapolation to the rest of the

[4] The model was validated against 42 homes belonging to BRE staff near Garston.

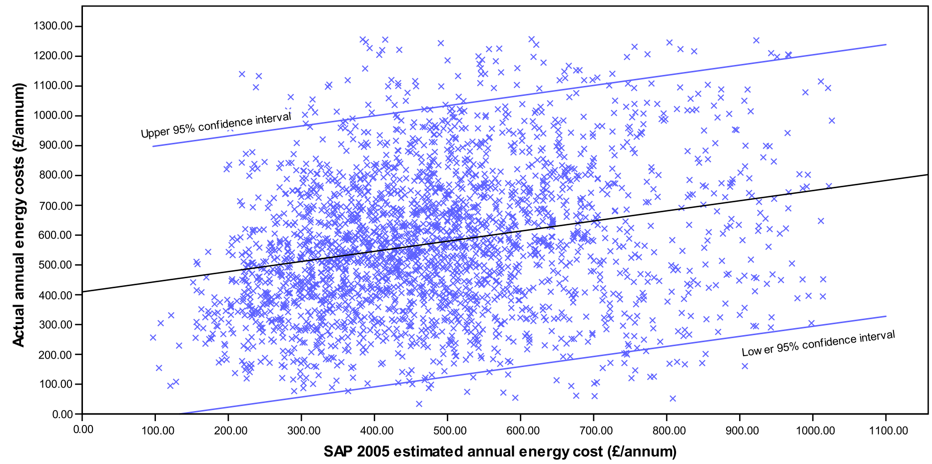


Fig. 6. Actual versus SAP estimated energy consumption.

UK building sector. For example, in order for BREDEM to reproduce statistically significant model estimates of energy consumption for the UK building sector, BREDEM would have to be validated against a sample of approximately 384 dwellings.[5] This has significant implications for the validation of SAP rates based on the same calculation routines used in BREDEM, where the most recent validation exercise was completed on just 19 dwellings. As far as the authors are aware there has never been a validation exercise conducted for BREDEM on a sample more than 45 dwellings or for a sample spanning any significant geographic-climatic region in the UK. Moreover, recent improvements to building codes have resulted in the construction of many high performance buildings. The energy consumption from this new generation of buildings has never been tested against BREDEM and SAP energy performance estimations [48].

Fig. 6 summarises data on the relationship between actual and modelled energy consumption, using the 1996 English house condition survey (EHCS) and the 1996 Fuel and energy survey (FES). The SAP estimates of energy consumption were taken directly from the 1996 EHCS. The scatter plot shows 3756 data-points and clearly shows the large variance between estimated and actual energy costs taken from metered energy consumption. It is expected that some of the variance can be explained by climatic and behavioural effects not included in SAP calculations. However, with such a wide confidence interval and weak statistical significance of slope, the variance between actual and estimated energy costs cannot be ignored. This raises serious questions about the legitimacy of SAP to estimate building performance more generally. In sum, the homogeneity and limited sample size severely limits the accuracy and robustness of these models to estimate energy performance from UK dwellings. It is therefore concluded that a new generation of energy demand estimation methods is urgently required. These new methods need to take proper consideration of the heterogeneity of buildings within the UK building stock with appropriate post-validation testing of the models against statistically significant random samples of dwellings.

2.2. The development of SAP for new buildings

One of the most important outcomes from BREDEM was the establishment of a national rating scheme for buildings, now known as the standard assessment procedure (SAP). The development of SAP was conceived from a desire to provide a national energy-rating label for buildings and to address the confusion that had arisen from several private-sector energy rating schemes [59]. The original purpose of SAP aimed to address the following issues:

- enhance the role of building energy efficiency for all buildings sold and let;
- use the SAP rate as a trigger for improving the energy efficiency of buildings; and,
- introduce minimum SAP rates into the building regulations for the construction of new buildings.

Although SAP is calculated using very similar algorithms included in BREDEM, there are several important distinctions between these two models. First, BREDEM is foremost a tool for estimating the energy demand from a dwelling. This requires the input of physical building characteristics but also details about occupancy and weather that are generally location specific. The purpose of SAP however, is to give a standardised measure from which the energy performance of a building can be compared with other buildings in the UK. Therefore, as an indicator of relative building energy performance (as opposed to estimating energy consumption directly) SAP rates are estimated independent from occupancy, behaviour and weather characteristics, although, other European countries make very different assumptions about the standardisation of different factors (e.g., France has three different climatic zones).

The first version of SAP was developed in 1993 as a joint project by the Department for the environment (DOE) and the Building research establishment (BRE). It was developed using the annual BREDEM-9 model to independently rate, assess and compare the energy performance of a heterogeneous building stock. By 1994, SAP had been incorporated into part L of the building regulations and marked a step change in the way newly constructed buildings were rated and assessed. One of the main outputs of the new rating system was an energy efficiency index, ranging from 1–100, known as the buildings SAP rate. The SAP rate represents an estimate of the annual cost in £/m^2 for providing heating, hot water and lighting to a dwelling. The higher the SAP rate the lower the expected energy cost. As well as being independent of demographic, social and cultural factors, SAP is also independent of the ownership and efficiency of appliances and individual heating patterns and temperature set points applied by the occupants [60]. Such factors are known to contribute significantly to actual energy consumption [61].

A consolidated version of SAP1995 was published in 1998 (SAP1998) with improvements to the methodology being introduced in SAP2001, SAP2005 and SAP2009. In SAP2001 a carbon index was introduced to demonstrate compliance with new building regulations [62]; this was later adapted in SAP2005 as the dwelling CO_2 emission rate (DER) and the environmental

[5] This assumes a confidence level of 95% and a confidence interval of +/−5%.

impact rating (EI) [63]. The dwelling emission rate is calculated from a notional dwelling benchmark based on Part L of the 2002 Building Regulations [64]. The environmental impact (EI) rating is based on a dwelling's CO_2 emissions from heating, hot water, ventilation and lighting less any emissions saved from onsite energy generation technologies. The EI rating is calculated using the emissions factors for different fuel types. Like SAP, it is normalised to unit floor area and expressed on a scale from 0 to 100 so that the building's EI rating is essentially independent of dwelling size.

In SAP2005, a supplementary calculation for stamp duty land tax (SDLT) was added giving exemption of stamp duty for zero carbon homes. In this new version several improvements were made including: additional allowances for the effects of thermal bridging; an update to solar hot water heating calculations; new allowances for renewable energy technologies; the addition of energy used for lighting; and, a change was made to adopt more widely understood energy units (i.e., GJ to kWh).

From April 2006, new building regulations stipulated the use of SAP2005 for all newly constructed buildings. Among other things, the new building regulations replaced the requirement of U-values for estimating household energy efficiency with the dwelling carbon dioxide emission rate (DER). At the same time, the new regulations necessitated the need for SAP rates to be displayed inside newly constructed buildings. Through a conspicuous display of the energy performance rating of newly constructed dwellings, it was hoped the awareness of energy efficiency for purchasers, sellers, and occupants would increase, and therefore be an important factor in the sale of domestic buildings. The intention of this new policy was to ensure that energy efficiency ceased being a hidden factor that was difficult and expensive to determine and would become a transferable, transparent, and simple indicator for making investment decisions in new dwellings. This principle was extended to existing dwellings and led to the implementation of RdSAP and later energy performance certificates (EPCs) for existing dwellings.

Up until 2006, the focus of building regulations had been on the construction of new buildings, or those buildings undergoing major renovation. With legislation for the construction of new buildings firmly in place, a new rating scheme for existing buildings was urgently required. In 2006, the building regulations were once again amended to comply with the new EPBD [65]. This led to the introduction of approved document L1A for new build and L1B for existing homes including extensions. The outcome was a new version of SAP specifically targeting existing dwellings. The new assessment procedure, now known as RdSAP (reduced data SAP) substantially lowered the overall data requirement from previous versions of SAP. With this new rating system, average values about the building stock can be used when physical data for a dwelling is either missing or incomplete. Theoretically, this means that every home, no matter how old, can be given a SAP rating from which it is possible to create an energy performance certificate (EPC). Under new legislation [66], an EPC must be produced whenever a building is sold, constructed or rented out, showing the energy performance of the property and how it can be improved. The purpose of the new law was to allow buyers to make informed choices about the purchase or rent of a property during the early stages of the transaction, thereby affecting the decision of purchase.

The most recent modifications to SAP2009 include: monthly estimates for the demand of space and water heating; allowance for space cooling; explicit inclusion of parameter estimates for the thermal mass of a dwelling; improved methods for the calculation of boiler and heat pump efficiencies; improved calculation of thermal bridging; and updated weather data tables and CO_2 emission factors.

Despite widespread use, there is still much confusion about what BREDEM, SAP and RdSAP actually measure. BREDEM is a building physics model that estimates the energy requirements of a dwelling while ignoring the behavioural effects of occupants. SAP uses BREDEM algorithms and therefore also ignores human behaviour but estimates the economic efficiency of a dwelling using standardised data for climate, the number of occupants, internal temperature characteristics and energy prices. RdSAP is similar to SAP but uses a standardised set of assumptions about building characteristics such as age, typology, and heating systems for estimating building performance. Even so, the input data requirements for RdSAP are still significant and can take a trained assessor one day to complete approximately four assessments [67]. In sum, BREDEM is used to estimate building energy consumption while SAP and RdSAP are used to estimate building performance.

SAP remains the most important calculation procedure for assessing and certifying the energy performance of new buildings in the UK. It is therefore, imperative that SAP and RdSAP give the right signals for transforming the building sector. This will require methodologies that fairly and accurately measure building performance in an open, transparent and transferable way. Fig. 7 is a timeline showing how BREDEM and SAP have evolved over the last forty years. Instruments such as the Green Deal, Renewable Heat Incentive (RHI), and Feed In Tariff's (FITs) will only lead to greater reliance on BPEC tools and standards in the future.

2.3. Inter-European comparison of building performance and certification

The EPBD (2002/91/EC) was introduced by the EU Parliament in 2002 and has had a significant influence in bringing about much needed changes to building regulations in many MS and remains the most important legislative instrument at the EU level for reducing energy consumption from EU buildings [65]. Despite concerted efforts from EU officials, the long-term trend across the EU27 has remained relatively unchanged (Fig. 8). The large difference in emissions between countries as shown by Fig. 8, can be explained by differences in climate, relative per capita wealth, the size of dwellings and the number of occupants per dwelling, and varies significantly between different EU MS.

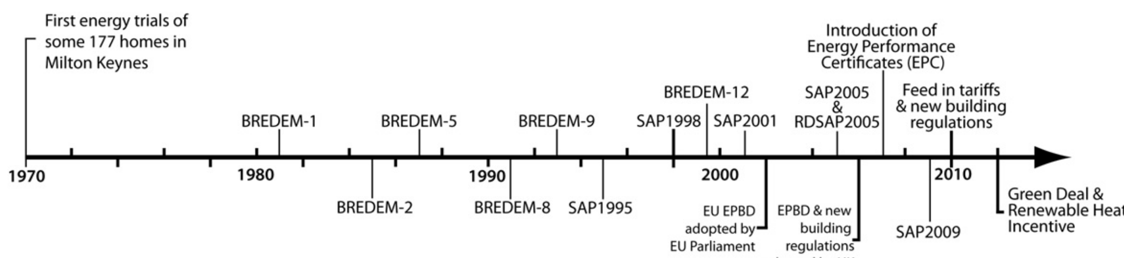


Fig. 7. Evolution of BREDEM and SAP.

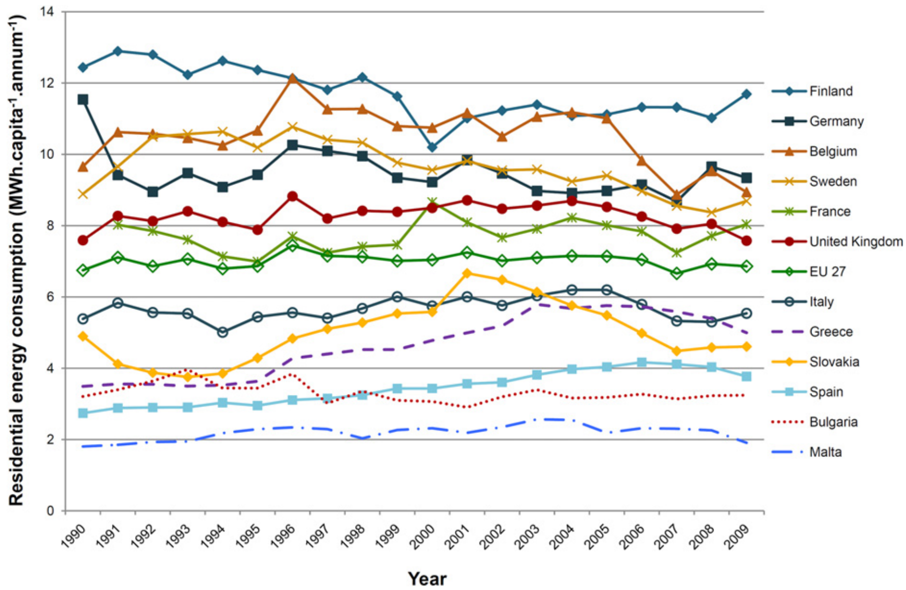


Fig. 8. Residential annual emissions for a per-capita basis for selected EU countries. (*Data source*: Eurostat 2011).

In the UK, the introduction of the EPBD came at a time when public awareness of climate change was increasing, as was political pressure to deal with fuel poverty. Thus, the introduction of a reliable rating scheme for both new and existing dwellings was acutely needed. The following section will compare and contrast different policy guidelines within the building sector for different EU member states, with particular focus on how the UK may learn from European experience.

As outlined by the European Parliament, the EPBD was designed to go beyond simply being a tool for the analysis and comparison of buildings to something that would form the basis of transforming the built environment across Europe. Under the principle of subsidiarity and proportionality MS were required to develop and implement measurement and certification standards for improving the energy performance of their building stock. Each MS was therefore given freedom to implement their own BPEC standards, the result was a plethora of different BPEC standards across all MS. Some 30 European (EN) and 24 International standards were drafted [68]. With the benefit of two years hindsight, the strategies adopted by different MS can now be assessed and compared.

A review of these schemes has highlighted some important differences. For example, some countries only consider heating while other countries include cooling needs as well as hot water, plug load, and lighting in energy and efficiency calculation procedures. There are also important differences in the level and type of information being collected. For instance, some member states use primary energy while others use final energy. Germany gives both primary energy and final energy statistics on the EPC [68]. While most MS give a grade in energy units (i.e., kWh/m^2 per year) some give additional units (i.e., CO_2/m^2 per year). The UK is somewhat unique in that it uses the final cost of energy to create a relative scale of building performance from 0–100. All these factors make it difficult to compare ratings across different MS. However, it is possible to look at different schemes across Europe and identify what instruments appear to work well.

When innovative products and technologies are not included in BPEC, it acts as a barrier to market uptake [70]. If a new technology or innovative system does not contribute to the calculation of the SAP rate, there is no motivation to include it in design, construction or renovation of a building [71]. It is therefore important that SAP procedures explicitly foresee the possibility of new technologies and innovative systems, which are not covered by the standard procedure. Countries like Portugal and Denmark offer loose frameworks, making it much simpler for new and innovative systems to be incorporated. However, there are disadvantages to this approach that include inaccuracies between anticipated versus realised energy savings. A further method of dealing with new and complex technologies is the 'equivalence approach' where equivalent technologies are used as proxies for unspecified technologies. To minimise disadvantages it is beneficial for any building performance standard to regularly make improvements to the calculation procedure or alternatively make allowance for technologies to 'prove' their efficiency levels before being included in performance estimates. If both calculated and metered energy consumption data were to be collected, the difference between these two values could assist in the determination of actual efficiency improvements offered by new technologies. Unfortunately none of the MS studied use both calculated and actual energy consumption for individual dwellings, making it difficult to test the impact of specific energy saving technologies across the building stock.

An important distinction between several EU schemes is the methodology used in the calculation of building performance. There are two basic methods. The first method is known as the 'estimation method' and is derived from the physical properties of the building. Average values for buildings of a similar type are sometimes used when information is missing (e.g. RdSAP). The second method is the 'measurement method' and uses actual energy consumption data to estimate building performance. Both methods have their own advantages and disadvantages. The estimation method is based on the physical properties of the building envelope and the efficiency of heating systems, thus detailed information about the building allows improvement diagnostics to be carried out. Another advantage of this calculation procedure is that standardised calculation procedures mean the calculated energy performance from buildings can be immediately compared with other dwellings. The time required to collect sufficient information about a building for this type of analysis is not negligible making it a much more costly process to implement. The price for carrying out an energy performance evaluation in Europe ranges from €40 to €1000 [69]. In the UK, the estimated cost is, estimated to be around £40 making it one of the most affordable schemes in Europe.

The measurement method, on the other hand, is quick and energy saving recommendations directly relate to the real energy consumption of the dwelling. This method however is adversely affected by occupant behaviour and because building certification supposedly represents an independent estimate of building performance and not the behaviour of occupants, standardisation of certification for comparison purposes across different buildings becomes problematic. A further complication of this method is that it makes the identification of building improvements difficult to assess as much less information about the physical properties of the building is collected and so the contributions of building characteristics and occupant behaviour cannot be separated. Clearly, the best approach is to combine both methods. There are presently four countries in the EU that allow users to choose between these two methods, these are: Finland, Germany, Luxembourg and Latvia. However, the full potential of combining estimated and measured energy consumption readings has not yet been fully exploited by any country.

Given the apparent success of the EPBD since it was introduced in 2002, and the huge potential remaining for improving the performance of buildings across Europe, a new version of the EPBD was recast and ratified by the EU Parliament [72]. The recast of the EPBD clarified, strengthened and extended the scope of the existing directive, requiring all new buildings to be 'nearly zero energy' by 2020. The definition of 'nearly zero energy' requires newly constructed buildings to have very high-energy performance with energy sourced from renewable sources produced on-site or in close proximity to where energy is finally consumed. This is in stark contrast to the strategy adopted in the UK requiring all new buildings to be zero-carbon by 2016. Given the controversy surrounding the definition of zero-carbon in the UK [73] and the difficulty in measurement and certification of zero-carbon policies [74], it is not surprising why the EU chose to use energy consumption as the measurement instrument instead of CO_2 emissions.

The subtle differences in policy and implementation strategies across Europe raises important questions about the availability of different schemes for meeting energy and climate change targets. While the UK methodology gives a certain amount of freedom for developers to source low carbon energy, it does not necessarily provide sufficient motivation to improve the efficiency of the building. Put another way, a building in the UK may continue to use energy inefficiently as long as it is taken from a low carbon source. This is in contrast to the recast of the EPBD that calls for clear strategies that focus on energy demand reduction and on-site renewable energy production. Although there are no specific targets for existing dwellings, the recast of the EPBD expects MS to develop policies and take measures that will stimulate the refurbishment of existing buildings and to inform the commission of these national plans.

3. Evaluation of energy performance certificates (EPCs)

A necessary and important output of carrying out building performance evaluations (e.g. SAP, RdSAP etc) is the energy performance certificate (EPC). In the preamble of the EPBD it states that the EPC is to form the basis of a package of integrated policy measures designed to transform the building stock across Europe. The EPC system therefore goes beyond being a simple tool for the comparison of buildings and serves as a policy instrument for reducing carbon emissions and transforming European buildings. One of the key principles of the EPBD is the stipulation that any building sold, leased or undergoing major renovations within the EU must have an energy performance evaluation and an up-to-date EPC.

The scheme is now functional in all MS and is regarded as successful in stimulating the transition to a more efficient building stock [69]. There are however, still logistical and economic considerations closely scrutinised by several MS. In the UK, SAP calculations have been mandatory for new buildings since 1995 and from 2007 it became compulsory for all buildings sold or leased to have an EPC [75]. The following section will therefore discuss the benefits and disadvantages of different strategies. Fig. 9 shows the layout of an EPC for England and Wales showing both the SAP rate and the environmental impact rating. The SAP rate is a discrete normalised scale with no connection to physical units. This is in contrast to the both the German (Fig. 10) and Italian (Fig. 11) versions that give a single continuous scale quoting actual energy

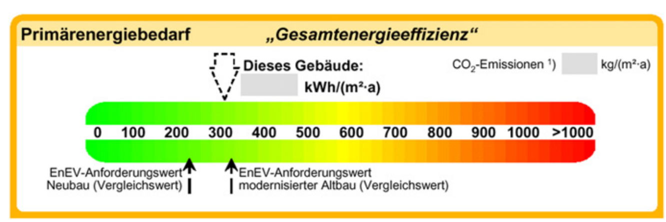


Fig. 10. German energy performance certificates.

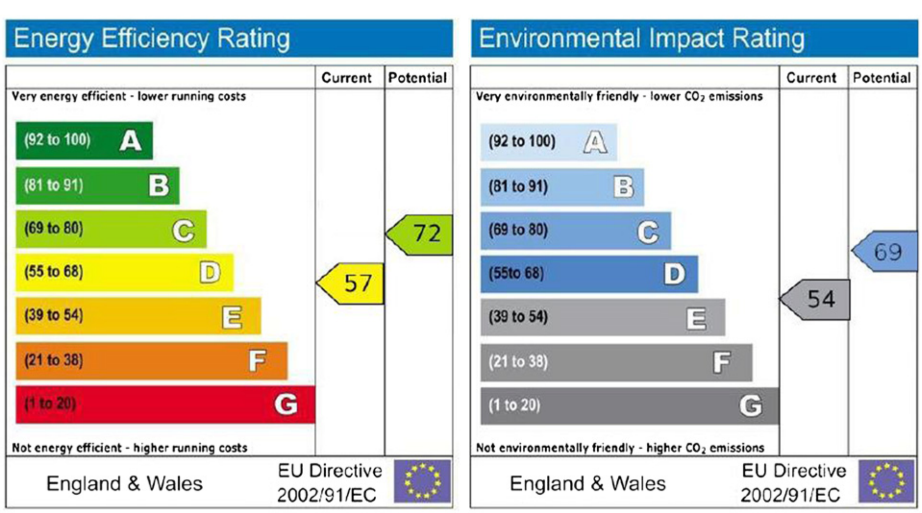


Fig. 9. SAP and EI rating for energy performance certificates (EPC) in England and Wales.

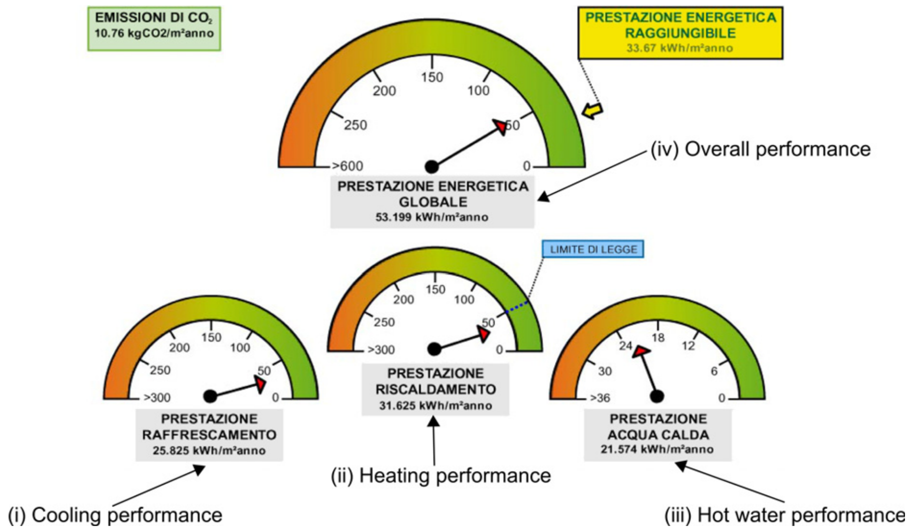


Fig. 11. Italian energy performance certificate showing a range of different measurements.

consumption in KWh/m^2). The German scale also gives estimates for the energy consumption of both new and old buildings for the same building type. The Italian EPC shows a range of different building performance measures; (i) cooling performance, (ii) heating performance, (iii) hot water performance, and (iv) overall performance. Both give an estimate of annual CO_2 emissions and the average performance of the building stock.

In the UK, EPCs provide important information to purchasers and renters about the performance of a building from which informed choices can be made. In essence, an EPC overcomes information asymmetry between the seller (who generally has good information about a building) and the buyer (who has limited information). Thus, EPCs act to facilitate the exchange of information between the buyer and the seller reducing the disparity between the *market price* and the *fair value* of a property [76]. This is a significant point considering research by *Wolseley (UK)* has shown over two-thirds of respondents would pay more for an energy-efficient home [77]. Even in cases where the seller may not have a good grasp of the energy performance of the property, an EPC may encourage the seller to improve the building performance in the hope it might increase the attractiveness of the property to buyers or renters who do place value on this type of information.

The way in which EPCs are delivered and the information they contain has considerable relation to the success of the policy instrument and ultimately whether the proposed measures are eventually adopted. The public perception of the EPC is as important to its effectiveness as the accuracy of the information contained on the certificate. In a study by Banks [67] it was found that the majority of sellers had a negative attitude towards EPCs. The common attitude was resigned acceptance, with misgivings about the whole process and speculation that EPCs were just another stealth tax applied by the government. Banks [67] found that estate agents had a similar view, speculating that the process was just a "big con" where they were left wondering what was gained from the process. As this type of attitude is so widespread, it may have an overall detrimental effect on the scheme. For example, homeowners are less likely to improve the performance of their home if they place no value on the results of the EPC and buyers will be less likely to consider EPC ratings when purchasing a home. User buy-in is thus essential for achieving market transformation, which in turn means there must be a clearly established relationship between the numerical value on the EPC and actual energy savings.

Banks [67] argues the costs associated with carrying out the assessments are one of the root causes of dissatisfaction. Once overheads are factored in, the cost of carrying out an EPC is estimated to be around £100. Banks [67] suggests that reducing the VAT rate from the full rate of 20% may go some way to reducing such apprehension. Somewhat perversely, the VAT on energy consumed for home heating in the UK, such as natural gas, is set at 5%, while costs associated with improving building efficiency (like EPC evaluations) are taxed at the full rate. This is a simple example where government policy is clearly sending the wrong message to consumers. Similarly, if building performance were linked to council tax rebates, the attitudes of buyers and sellers would likely favour improved energy efficiency.

In the UK, the full EPC contains more information than just the categorical A-G SAP scale. The certificate also includes an EI rating and information on the estimated running costs of the building broken down by service type. Average building performance of all UK dwellings is also included (grade E), but such information is only vaguely helpful. If the average performance of a building in the same building category (i.e., same building type, age and construction material) were given instead (similar to the German standard), it would give owners a better indication of whether their property was over or under-performing for that particular building category. Such an addition might stimulate an increase in energy efficiency, as buyers and letters tend to make comparisons within a category of buildings rather than across them.

As stipulated in the EPBD, EPCs are required to include recommendations for cost-effective building improvements. This is probably the most valuable information contained on the EPC. These are separated into 'lower cost measures', 'higher cost measures' and 'other solutions'. Lower cost measures typically cost less than £500 while higher cost measures typically cost more than £500. The 'potential' column in the EPC certificate only includes improvements from lower cost measures. The category 'other solutions' generally includes options that are more expensive and have much longer payback periods. The cost-effectiveness of options is estimated using a simple payback calculation. Although this is the easiest approach, it does have several drawbacks. Simple payback is sensitive to changes in costs and is a poor estimate of costs that arise in the present and savings that accrue in the future. A more accurate method would use net present value (NPV) or internal rate of return (IRR) calculations to allow for the time value of money. In addition, the anticipated future prices of fuels should be included in calculations as the effect of rising (changing) energy prices has a

significant effect on the cost-effectiveness of different energy efficiency measures. A government certified annual forecast of future energy prices could be used to improve the cost estimates of different efficiency measures. Simply assuming existing energy prices continue at current prices is incorrect and leads to erroneous results that underestimate the cost effectiveness of building improvements.

An important component of the EPC is the list of cost-effective improvements listed on the certificate. Research by Oxera has shown that most residents have little or no knowledge about the characteristics of energy efficiency, including costs [78]. For example Oxera showed that only 8% of respondents were aware of accreditation schemes for existing domestic insulation installers and significantly over estimated both the time and cost of installations. This highlights the importance of providing an indication for the true costs and savings to a dwelling. Information concerning actual building running costs is most relevant to new building occupiers. Unfortunately, only estimated running costs are provided for a dwelling on present EPC's. Providing new occupiers with information on the actual energy consumption of a dwelling based on metered energy consumption readings will give new occupiers a much better picture of the real performance of a dwelling. With information about a dwelling's actual energy consumption, improved estimates about anticipated savings can be made and therefore more accurate recommendations for the most cost-effective energy efficiency measures given.

In order to work effectively the EPC must be available to new occupiers as early as possible in the decision making process. Because many responsibilities for carrying out EPC duties fall on estate agents, solicitors and private landlords, the success or failure of the scheme lies with these professionals. In a study by Banks [67] it was found that many professionals were not fully adhering to the scheme guidelines or simply doing the bare minimum to meet regulatory compliance. Banks [67] found statutory regulations were too relaxed, reducing the potential effectiveness of the scheme. One prime example is the absence of any requirement to show the EPC until right before a new contract was signed, at which point the decision to purchase or lease the property had already been made. This reduces the power of the market to discriminate between homes with different energy performance characteristics. One way to overcome this shortcoming is for the energy performance rating to be included with any advertisement, or marketing material aimed at selling or leasing a property. With the introduction of the recast of the EPBD [79] due to be enforced by all MS by January 2013, building performance ratings will be mandatory on all property advertisements. This will likely lead to greater awareness and use of EPC ratings for comparing building performance values, shifting demand within the market to favour dwellings with higher energy efficiency characteristics [80].

The evidence presented suggests that actual energy consumption and calculated energy consumption are very different and sometimes differ by as much as twice to three times what appears on EPCs. Although much of the variance can be explained by missing behaviour and sociodemographic variables, this may have damaging effects on the credibility of building performance standards. For example, anecdotal evidence suggest users of this information expect building performance evaluations to provide an accurate representation of energy consumption, energy efficiency and environmental impact. Unfortunately in many situations this is not the case as will be described in the following section. Therefore, providing sufficient detail on the certificate on what the indicators are actually measuring will go some way to alleviating these shortcomings.

4. A critique of SAP

In previous sections, we discussed the evolution of building simulation models and their role in developing summary indicators of building performance. We then looked at the introduction of the EPBD and the effect this was having on transforming the built environment across Europe. Our attention then focused on the importance of EPC and the differences in certification accross different EU countries. Next, we will discuss the strengths and weaknesses of the SAP methodology adopted in the UK and highlight how BPEC might be improved so that building evaluations better predict actual performance and hence can be used to identify the most cost-effective efficiency improvements.

SAP ratings attempt to measure the annual unit cost of space and water heating from notional assumptions about heating patterns and internal temperatures. Because SAP is an index calculated from a collection of many different building elements it allows developers to mix and match different building components to meet SAP requirements, often resulting in sub-optimal outcomes. For example, improvements made to the building fabric might be sacrificed for an improved heating system, such as a condensing boiler. Although, in theory, this leads to cost-optimal solutions at the time of construction for meeting minimum SAP requirements, it results in sub-optimal solutions for building performance over the life of the building. This is emphasised in Table 1 where the additional marginal cost of a condensing boiler over a standard boiler at the time of construction is negligible, making it an obvious choice for a developer wishing to meet minimum SAP requirements. If on the other hand, the lifetime emissions from competing energy efficiency measures are compared, cavity wall insulation and roof insulation offer the most cost-effective CO_2 savings over the life of the measure. Nevertheless, a developer trying to minimise costs

Table 1
Typical costs and CO_2 savings for UK dwelling[a] *Data source*: [24].

	Energy consumption	Difference in cost at installation	Annual energy savings	Lifetime	End of life carbon savings	Net annual cost[b]
	kW h/year	£	£/year	years	$kgCO_2$/year	£/year
A/B rated boiler	14,623	£50	57	15	5,610	−£53
With roof insulation	11,687	£339	87	40	27,840	−£71
With cavity insulation	10,783	£406	133	40	35,480	−£114
Glazing E to C rated	14,542	£253	14	20	1,760	−£4
Hot water cylinder insulation	14,059	£20	29	10	1,945	−£27

[a] This assumes the building has an annual energy demand of 15 MW h/year with annual discount rate, r, of 3.5%.
[b] Net annual cost (NAC) is a measure of cost-effectiveness. A negative NAC indicates that a measure is cost effective (i.e., over the life of the technology the return on the investment is greater than cost of the initial investment), whilst a positive value indicates the investment is not cost-effective. $NAC = EAC - S$; where S is the annual savings of the measure and $EAC = Cr/\left[1-(1+r)^{-n}\right]$; where C is the capital cost of the measure, r is the annual discount rate (3.5%) and n is the life of the measure in years.

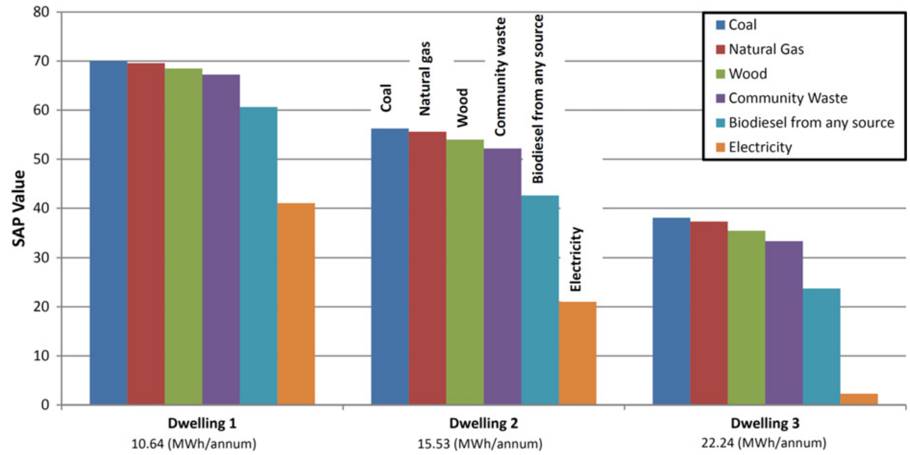


Fig. 12. Effect of fuel type on SAP.

whilst meeting minimum SAP compliance, will always choose the option that has the least capital cost at the time of construction in order to meet regulatory compliance. Alternatively, if the net annual cost (NAC) method were used instead to assess and compare technologies over the life of different measures, it becomes possible to compare the most cost-effective and the most carbon efficient technologies.

The main reason for the large differences in the NAC between different technologies (Table 1) is that different building efficiency measures have differently estimated working lives (e.g., a condensing gas boiler has an expected life of 15 years while the installation of cavity wall insulation is expected to last more than 40 years). These factors are left out of present SAP calculation procedures that only estimate the building's present day performance and incentivise investment calculated from the cost difference at the time of installation. Even though Table 1 represents an improvement on existing methods but neglects to include the additional savings from making refurbishments at the time of construction thus reducing transaction and labour costs. For example, a study by the Energy Saving Trust [81] shows that it is more cost-effective to install efficiency measures during construction or refurbishment than doing so haphazardly over the life of the building. This is due to the added costs of time and labour owed to piecemeal improvements. If the additional savings made by installing efficiency measures at a single point in time (as opposed to haphazardly) the overall economic performance of carbon saving measures will improve and reduce the total cost of investment. Such benefits need to be included in estimates of cost effectiveness.

In Fig. 12, three dwellings are chosen to represent the building stock in England. Dwelling 1 represents a home at the 25th percentile of energy consumption, Dwelling 2 is taken from the 50th percentile and Dwelling 3 is taken from the 75th percentile. The SAP value for each home is calculated using the SAP2009 methodology with a standard typical floor area of 90 m^2. One-third of each dwelling's total energy consumption is assumed to be met by electricity with the remainder being supplied by coal, natural gas, wood, community waste (i.e., waste-to-energy) or bio diesel (Fig. 12). The only exception is for homes that use electricity for heating, where it is assumed electrical resistance heaters supply all the heat in the dwelling.

The main conclusion from Fig. 12 is that fuel type plays a very important role in determining a building's overall SAP rate. Strikingly, fuel type appears to make even more difference to SAP than improving building efficiency and reducing energy consumption. This is in large part because the more carbon intensive fuels tend to be less expensive per unit of energy consumed. Unfortunately, this situation may lead to perverse

Table 2
Fuel prices and emissions factors used in SAP2009.

Fuel Type	Fuel price (p/kW h)	Carbon intensity ($kgCO_2$/kW h)
Coal	2.97	0.301
Natural gas	3.1	0.198
Wood	3.42	0.008
Community waste	3.78	0.040
Bio diesel from any source	5.7	0.047
Electricity (standard)	11.46	0.517

incentives where it is possible to improve a building's SAP value by switching to coal from a less carbon intensive fuel such as wood or bio diesel. In this example, Dwelling 1 can jump from having EPC rating of E to C simply by switching from electricity to coal for heating without any other building efficiency improvement. In fact, because coal is one of the cheapest fuels used for heating it gives the highest SAP rate when compared with all non-renewable fuel types. This occurs because SAP is a measure of the economic performance of a building and not a direct measure of energy efficiency. It uses energy cost as a surrogate for energy consumption and/or carbon emissions, making it better suited to policies aimed at reducing fuel poverty than at reducing energy or carbon. Within the SAP calculation procedure, energy consumption is estimated from space heating, water heating and electrical lights and appliances. The annual fuel bill is then estimated using standard prices from SAP2009 (Table 2). It is from the total annual fuel bill that the energy cost factor (ECF) is calculated using Equation (1.1).

$$\text{ECF} = \frac{C \times \mu}{(45 + A)} \tag{1.1}$$

$$\text{for ECF} \geq 3.5,\ \text{SAP}_{2009} = 117 - 121 \times \text{LOG}_{10}(\text{ECF})$$
$$\text{ECF} < 3.5,\ \text{SAP}_{2009} = 100 - 13.95 \times \text{ECF} \tag{1.2}$$

In Eq. (1.1) ECF is the energy cost factor; C is the estimated annual energy bill for a property, μ is the GDP deflator that allows SAP values to be compared across different years, and A is the total floor area for the dwelling. Thus, the ECF is proportional to the anticipated annual fuel bill on a per m^2 basis. A log transformation is then applied to the ECF to convert it into a SAP rate and put it on a scale from 0 to 100 (Eq. 1.2).

The effect of including prices in the calculation of SAP distorts the overall assessment of building efficiency and may undermine legitimate intentions to make buildings more energy efficient. Another unintended consequence of using energy prices is

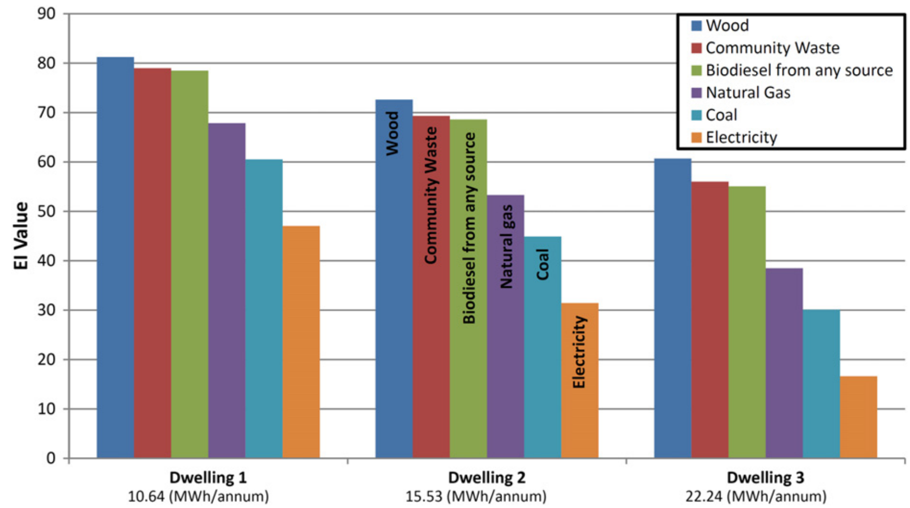


Fig. 13. EI ratings for different fuel types.

that energy prices fluctuate, sometimes dramatically. Although changes to energy prices over time, within a basket of different fuel-types are captured by the GDP deflator, the relative price difference between fuels is not captured. For example, if the price difference between electricity and other fuels increase, the relative difference in SAP rates will also increase.[6] The result is that SAP values may fluctuate between successive SAP models, not because of changes to building performance but simply because of differences in the market price of fuels assigned. Another downside of the present SAP methodology is that it fails to consider the relative CO_2 emissions from different fuels. From Fig. 12 renewable fuels such as wood and bio diesel only contribute to SAP values through price; thus, if the price of renewable fuels increase, the effect will be a subsequent decrease in the SAP score for dwellings that use these renewable fuels. This clearly contradicts one of the intended purposes of SAP which is to reduce energy consumption and lower CO_2 emissions. Absent a significant tax on carbon emissions (and thus increasing the price of fossil fuels) this problem with SAP will remain.

Thus far, we have shown SAP is a measure of the cost effective performance of a dwelling and not a measure of energy efficiency per se. Now it will be shown that SAP is also a poor measure of economic efficiency. Recent changes introduced into SAP2009 allow dwellings to offset their energy consumption through the generation of electricity through micro-generation technologies. If electricity produced on-site exceeds the energy requirements of the dwelling it is given a SAP rating over 100. Under these circumstances it is therefore possible for a dwelling with very low energy performance to get a high SAP rating if electricity is produced on-site from the installation of PV, micro wind or microCHP. The marginal abatement cost for generation of electricity from these technologies is known to be higher than that of energy saving measures [82]. Moreover, as the cost of electricity produced by micro-generation technologies is not included in SAP calculations, SAP does not accurately estimate the cost of energy coming from micro-generation and merely inflates the SAP rate proportional to the amount of energy generated. By allowing such technologies to contribute to the overall SAP rate, SAP moves even further from being about efficiency and cost. It also undermines the purpose of the EI rating established for the purpose of giving feedback on carbon emissions. Furthermore, as SAP is inherently designed to be independent of geographic location and human behaviour, the estimated cost of energy is even further distorted.

At present, SAP is not set up to handle reimbursements from FITs or the RHI from micro-generation technologies. Incorporating the financial benefits of FITs and the RHI into SAP will require significant changes to the way SAP is presently calculated. Cost rebates for different technologies vary, complicating energy cost estimates, and therefore complicating the estimated SAP rating. Moreover, most technologies qualified to receive a financial rebate under present FIT and RHI assumptions are subject to degression rates[7] thus changing the level of subsidy available depending on the year the technology was first installed. This unnecessarily adds several layers of avoidable complication to SAP calculations. If SAP removed energy prices from its calculation procedure altogether (like most other European countries) SAP would be a much better estimate of a building's energy efficiency rate represented in (kWh/m^2) and would be a better means for identifying strategies for reducing energy use and carbon emissions.

The SAP calculation procedure also assumes that electricity generated from PV is co-incident with average demand, therefore reducing net electricity consumption. This is not always true, as solar energy occurs during the day when occupants are typically at work requiring electricity to be exported to the grid. Simply assuming average solar capacity factors across the country also leads to erroneous results, as different parts of the country receive different levels of radiative energy from the sun. Another peculiarity of allowing on-site electricity production to contribute to SAP rates is that there is no allowance for on-site heat production, aside from energy produced through CHP district heating schemes [83]. The effect of recognising onsite electricity production but not heat is that it benefits expensive electricity technologies and therefore benefits wealthy households that can afford to invest in micro-electricity generating technologies. In addition, there is no account given to dwellings that may be on a renewable electricity tariff. If SAP aimed to be internally consistent, it would be possible to offset energy consumption using other forms of renewable heat generation such as homes heated by wood stoves, biomass or community heating supplied by renewable sources.

[6] Presently fuel prices are updated in the SAP calculation procedure every six months.

[7] Degression is the rate at which the levels of a tariff reduce over time allowing for the cost reductions of a technology as volumes build over time.

At present, the combustion of these fuels contributes to energy consumption and therefore has a negative impact on SAP rates.

Under present SAP assumptions Solar Hot Water Systems (SHWS) connected to central heating systems do not improve SAP rates. It is only solar thermal systems connected to hot water systems that contribute to SAP rates. Energy consumed by hot water systems represent just 20% of home energy requirements, severely limiting the potential for solar thermal to contribute to a dwellings total energy requirement. This is despite the significant potential for solar heating during autumn and spring to contribute to central heating requirements. Because of this, any additional solar hot water produced over and above the hot water demand requirements cannot contribute to central heating demand reduction within the SAP calculation for central heating and therefore limits the overall contribution that solar heating systems can make to improve the overall SAP rating of a dwelling. Unlike PV, solar heating systems have the advantage of storing heat in hot water cylinders until heating is required. Lastly, Banks [67] revealed that SAP calculations were only capturing 25% of the potential energy savings from solar heating. SAP calculation procedures would therefore benefit greatly from improved handling of solar heating systems.

In order to overcome the limitations of SAP, the environmental impact rating (EI) was created and designed to sit beside the building's SAP rate on the EPC. Instead of using energy prices (like in SAP) the EI rating uses emissions factors from different fuel types. Using the same dwellings from Fig. 12, we have recalculated the EI rating.[8] An advantage of EI ratings over SAP ratings is that they include CO_2 emissions factors, but a disadvantage is that they fail to give an accurate measure of building efficiency. For example, in Fig. 13 homes that use renewable fuels such as wood, will receive a high EI rating despite how much energy is consumed overall. For homes that use electricity from the grid, the EI rate is even more problematic as it completely depends on the carbon intensity of the national grid (presently estimated at 0.517 $kgCO_2$/kWh), which is predicted to change markedly over the coming several decades. Finally, having two indicators on the EPC adds to the confusion about what these indicators actually measure and which ones should be used as a measure of energy efficiency or as a means to identify strategies of reduction of energy costs, energy use or carbon emissions, all of which are distinct policy aims.

The effect of human behaviour on household energy consumption is known to be significant [16,18,61] and estimated to account for 51% of the variance in heat demand and 37% of the variance electricity demand for different energy users [84]. Behaviour is also one of the biggest uncertainties in estimating household energy consumption. Even so, most building performance models do not incorporate human behaviour in their analysis [85]. With the rollout of smart-meters and other technologies that integrate with human behaviour, it will be increasingly important to allow for the effects of these new technologies when estimating building performance. In addition, the time of day that energy is consumed is also important [86]. For example, electricity consumed during peak periods will have different carbon emissions factors as the electricity generation mix fluctuates. As new demand is placed on the electricity system, the electricity mix changes as does the marginal generating plant. The more demand on grid fluctuates the more important it will be to allow for this effect in calculating the emissions from discrete homes, each having varying energy demand profiles. The incorporation of emission factors for varying energy use patterns into building calculation procedures could incentivise people to shift their demand and therefore reduce overall emissions [87].

[8] For ease of comparison we make the assumption that one-third of total energy comes from electricity and that the total floor area for each dwelling is $90m^2$.

5. A critique of RdSAP

While SAP is primarily designed for assessing the performance of newly constructed buildings, RdSAP is designed for assessing the performance of existing buildings. RdSAP uses the same underlying algorithms as SAP, and therefore suffers many of the same criticisms. Unlike SAP where energy prices are updated every six months, energy prices in RdSAP are updated every three years. But what makes RdSAP significantly different from SAP is that it is designed for use by someone with limited knowledge of building energy analysis. This means RdSAP requires assumptions to be made about the energy consumption based on the type and age of the building; hence it is an indication of energy consumption across large populations of buildings with similar general characteristics, rather than being specific to a particular building. All buildings assessed in RdSAP are assumed to be located in middle England and have typical occupancy rates calculated as a function of floor area. There are also assumptions about heating requirements, where all rooms are heated to a comfortable level (21° in living areas and 18° elsewhere) with a high standard of hot-water heating. Thus, there is a trade-off between model simplicity, accuracy and comparability with other dwellings that may lead to confusion and produce grossly inaccurate estimates about a particular buildings energy consumption and overall energy performance (see Fig. 6). Given the assumptions made by RdSAP and the large variance between different householders' actual energy use within a building energy category, errors can be introduced for specific buildings even when estimates of means across categories are correct. For example, dwellings in colder parts of the country should expect their heating bills to be higher than those predicted by RdSAP.

This use of category averages of performance limits the potential of RdSAP to make sound recommendations for improvements. For example, within RdSAP all homes constructed after 1983 are assumed to have cavity wall insulation; if a domestic energy assessor (DEA) learns this is not the case, there is no opportunity for including this as a recommendation for improvement, thus missing a key opportunity to improve the buildings performance. Allowing assessors to enter known information about a dwelling will give better insights into recommendations for improvements, thus missing a key opportunity to improve the buildings performance. Allowing full SAP assessments to be carried out on existing dwellings, will provide more accurate estimates of building performance when required. Additionally, some of the default assumptions in RdSAP are the most cost-efficient options, giving no motivation for assessors to enter the correct energy characteristics. Defaults should therefore be set as the worst performing alternative; thus rewarding occupiers and developers for making the extra effort to calculate the true performance of a property. The pasivhaus standard (PHPP) in Germany adopts a similar principle, rewarding occupiers for making more detailed energy estimations [88].

6. Discussion and conclusions

In this paper, we have shown the calculation procedures used within SAP and BREDEM have never been robustly validated against a statistically significant sample of dwellings that represent the UK residential building stock. Moreover, the few studies that have been completed use a relatively homogenous sample of dwellings from a confined geographic-climatic area. Although some of the variance between calculated and actual energy consumption can be explained by differences in behaviour and geographic location, the

Table 3
Effect of policy instrument on policy objective.

Policy instrument	Impact on policy objective					
	Lower CO_2 emissions	Improve fabric efficiency	Lower energy consumption	Reduce fuel poverty	Increase renewables	Improve security of energy supply
EPC	Medium	Medium	Low	Medium	Low	Low
SAP	Low	Medium	Low	Medium	Medium	Low
RdSAP	Low	Medium	Low	Medium	Medium	Low
EI	High	Medium	Low	Low	Medium	Medium
FIT	High	Low	Low	Low	High	High
RHI	High	Low	Low	Low	High	High
GreenDeal	High	High	High	High	Low	Low

unexplained variance remains substantial. As both the SAP rate and the EI rates are provided on a scale ranging from 0 to 100 with no evident link to physical units of performance, there is no relevant feedback to the user about what this means in terms of their relative energy consumption or emissions and how this may compare to other dwellings of a similar building type with different energy efficiency measures applied. Many MS in Europe have opted to retain the original energy units on EPCs (i.e., in kWh/m^2 see Fig. 10) so that occupiers of dwellings are encouraged to think about energy consumption in original units, therefore increasing awareness and perhaps changing energy practices. The EI rating on the other hand only considers the emissions factors of different fuel types, and provides these as an areal density (emissions per square metre) that is of limited use in assessing movement towards national emissions reduction targets. This measure therefore allows profligate energy consumption as long as it is low carbon, ignoring issues of resource conservation and fuel poverty.

Energy performance certificates are a critical component of the BPEC system. The energy rating of a dwelling needs to be made explicit at the earliest stages of the leasing and buying process. Certificates need to be clear and well trusted by owners and new tenants or their effectiveness as a policy instrument is reduced. The present recommendations included on an EPC for improving building performance are based solely on estimated energy consumption and crude assumptions about the future price of different fuels. Including actual energy consumption data on the EPC will act as a reality check against which calculated energy performance can be compared. Using metered energy consumption data, for cost-effective efficiency recommendations (instead of estimated performance) will improve the accuracy of estimating the cost of energy saving technologies. Building performance recommendations will also benefit from improved government backed energy price forecasts and lifetime cost effectiveness calculations estimated using the net annual cost method.

It is argued that SAP and RdSAP confound cost-effectiveness, energy efficiency, environmental performance and GHG emissions adding unnecessary complexity and confusion to the SAP calculation procedure. As a result it is not clear which of the many national policy aims – reducing fuel poverty, increasing energy efficiency, decreasing overall energy use, or reducing carbon emissions – is being captured by the various performance measures. This then leads to confusion and disconnect between performance measures, policy instruments and policy objectives and which of the relevant policy aims is being improved by a paritcular strategy. Inconsistency across different approaches then leads to perverse incentives. For example, dwellings that switch to low cost fuels such as coal are rewarded with higher SAP rates despite the adverse implications for carbon emissions reduction.

As clearly shown in Table 3, there are large differences across policy instruments for the effect they have on policy objectives. At present policy instruments are used haphazardly to meet multiple policy objectives. Unfortunately this approach leads to unpredictable and possibly ineffectual outcomes. Redesigning BPEC tools so that they target specific policy objectives may lead to more cohesive and productive outcomes. For example, including separate indicators on an EPC for energy consumption (kW h/m^2), CO_2 emissions (kgCO_2/m^2), and energy costs (£/dwelling) will provide a much greater level of information about a dwelling allowing users to make more well informed investment decisions. Matching measurements with policy objectives reduces confusion and may improve the effectiveness of policy instruments. If required, an additional aggregate indicator that transparently combines each of the three sub-indicators could then be used to assess the overall performance of a dwelling against a combined set of policy objectives. Using this approach makes it possible to transparently represent the importance of each sub-indicator using predetermined weights. Policy makers thus have the power to reflect the importance of policy objectives through the relative size of different weights on the EPC.

In addition to targeting policy instruments to match policy objectives there is also a clear need for more detailed information about the building stock to be made publicly available for research purposes. This is particularly true for data at the dwelling level representing actual energy consumption. These data will allow comparison of estimated and actual performance of buildings, enhancing confidence that such performance measures are useful in identifying the most cost-effective strategies for energy and carbon reduction. Such a statistical database will allow a set of criteria to be established so that buildings can be benchmarked against buildings of the same type. It will also allow researchers to monitor the progress being made in the transformation of the buildings sector.

In conclusion, SAP, RdSAP and EPCs are critical for the transformation to a zero-carbon building stock. It is important that these indicators accurately measure building performance and are then actively used for setting and meeting policy objectives. This requires calculation procedures that are robustly validated; standards that measure and compare the right factors; EPCs that are understandable and reliable and drive decision making; and finally, a system of data gathering and research methods that provide feedback into understanding and transforming the building stock.

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